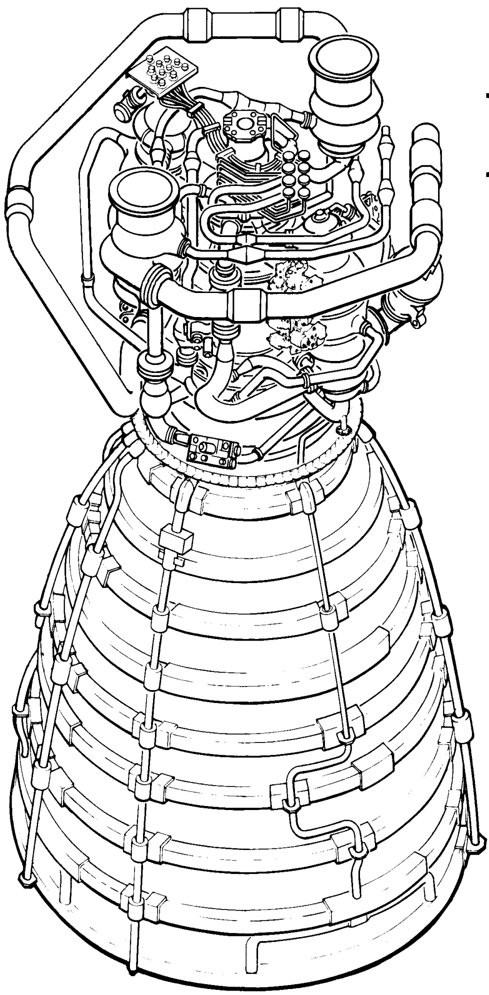

Endeavour STS-108

Space Shuttle Program

SSME Flight Readiness Review

November 15, 2001

G. HOPSON

Endeavour STS-108

Agenda

- **Major Components**
- **Engine Performance**
- **First Flight ECPs -** None
- **Special Topics**
  - Engine 2052 Foreign Object Debris
  - LPOTP Nozzle Vane Cracking
- **Material Review Reassessment**

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SSME Major Components

Engine	ME-1 (2049) *Block IIA*	ME-2 (2043) *Block IIA*	ME-3 (2050) *Block II*
Last Hot-Fire	**STS-100**	**STS-100**	**902-793**
Powerhead	6019	6013	6006
Main Injector	6011	2033	2032
MCC	6015	6006	6023
Nozzle	4028	5004	5007
Controller	F41	F55	F53 (1)
HPFTP	6017	6015R4	8017
LPFTP	4210	2130R3	6104
HPOTP	8016R4	8021	8025R1
LPOTP	2133	6001	2325

(1) Changes from last hot-fire.

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Predicted SSME Ignition Confirm Margins

Parameter	Margin Sigma		
			--- Block II ---
	ME-1 (2049)	ME-2 (2043)	ME-3 (2050)
HPFTP Minimum Speed	4.7	7.7	3.2
Min/Max Ignition Pc	**[1.9]**	5.2	3.8
Antiflood Valve Min Open	25.5	27.0	22.3
HPFTP Max Turbine Temperature	4.9	9.7	5.3
HPOTP Max Turbine Temperature	3.4	4.0	5.4
HPOTP Min Turbine Temperature	7.9	8.5	8.9
Preburner Max Purge Pressure	29.4	29.5	29.2
POGO GOX Min/Max Pressure	20.1	9.8	12.8

[ ] Less than 3 sigma margin, however,
3.2 sigma using a run-to-run database

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Predicted SSME Performance at 104.5% P.L.

At Engine Start + 200 seconds
(MR = 6.032, OPI = 69 psia, FPI = 28 psia)

			--- Block II ---
	ME-1 (2049)	ME-2 (2043)	ME-3 (2050)
Parameter	Sigma	Sigma	Sigma
HPFT Disch Temp A, Deg R	0.7	**b** **[-2.9]**	**c** **[-2.3]**
HPFT Disch Temp B, Deg R	0.9	**b** **[-3.3]**	c -1.5
HPOT Disch Temp A, Deg R	1.1	-1.0	-1.1
HPOT Disch Temp B, Deg R	1.8	-0.1	-0.4
HEX Interface Temp, Deg R	1.1	-0.6	-0.9
HPFTP Speed, rpm	0.0	-0.9	**c** **[-2.6]**
LPFTP Speed, rpm	-1.0	-0.8	-0.9
HPOTP Speed, rpm	-1.9	-0.2	1.0
LPOTP Speed, rpm	1.0	-0.3	0.3
OPOV Position, %	**a** **[3.0]**	-0.5	-0.4
FPOV Position, %	1.3	-0.8	-0.8
PBP Disch Pressure, psia	-1.3	0.2	0.9
HPFTP Disch Pressure, psia	0.2	0.4	-1.8
HPOTP Disch Pressure, psia	-0.5	0.4	1.3
HPFTP U/N	6017	6015R4	8017
LPFTP U/N	4210	2130R3	6104
HPOTP U/N	8016R4	8021	8025R1
LPOTP U/N	2133	6001	2325

[ ] Exceeds database two sigma
a Effect of high efficiency HPFTP and low PBP Discharge Pressure
b Unique powerhead influence, consistent with past operational history
c High efficiency HPFTP

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Predicted Redline Margins at 104.5% P.L.

Parameter	Margin Sigma		
			--- Block II ---
	ME-1	ME-2	ME-3
HPFT Discharge Temp ChA, Deg R	5.4	10.7	8.6
HPFT Discharge Temp ChB, Deg R	6.2	12.5	8.8
HPOT Discharge Temp ChA, Deg R	6.3	7.0	7.6
HPOT Discharge Temp ChB, Deg R	7.4	8.1	8.9
HPOT Discharge Temp ChA, Deg R	7.0	5.3	5.8
HPOT Discharge Temp ChB, Deg R	7.2	5.4	5.9
HPOTP IMSL Purge Pr, psia	5.9	6.2	8.1
HPFTP Coolant Liner Pressure, psia	16.6	16.0	---
Low MCC Pc, psid			
Command-ChA Avg	21.9	20.3	22.4
Command-ChB Avg	25.4	23.3	25.9
FASCOS			
HPFTP	15.1	14.1	8.4
HPOTP	34.6	33.6	33.6

E2052 Foreign Object Debris

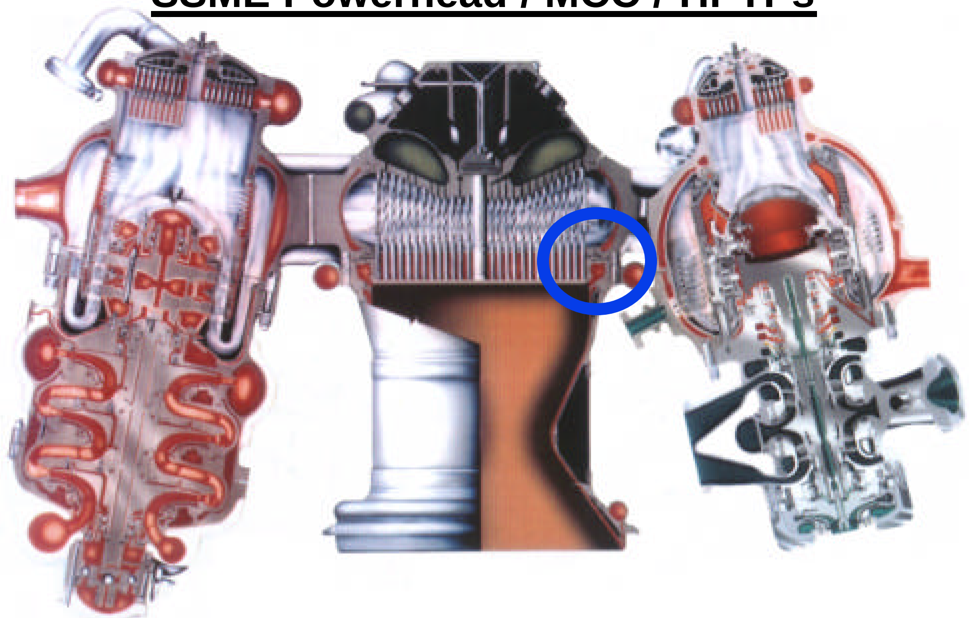
Broken Burr Ball Bit

- **Issue**
  - FOD found in Engine 2052 / Powerhead 6009
- **Background**
  - Burr ball bit found in main injector hot gas cavity during routine STS-105 post flight borescope inspections
    - Lodged in LOX post outer row secondary faceplate retainer hole
      - Piece size: .078” dia x .380” long (.388 grams)
    - Piece retrieved - inspections revealed no discernable hardware damage
  - E2052 / PH 6009 Operational History
    - E2052
      - 5 starts / 2713 seconds (4 flights)
    - PH 6009 (used with Block IA E2039 and Block IIA E2052)
      - 11 starts / 5397 seconds (8 flights)
  - Engine performance as expected - no performance or structural anomalies

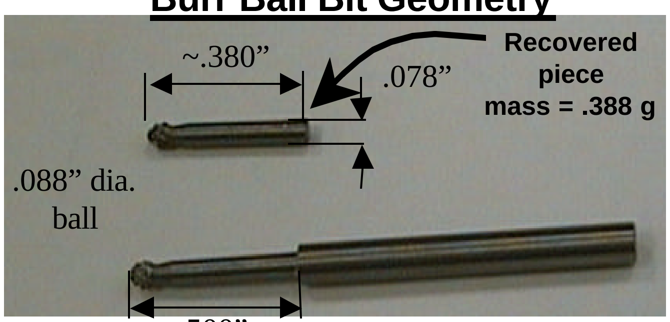
E2052 Foreign Object Debris

Engine Cross Section / Hardware Geometry

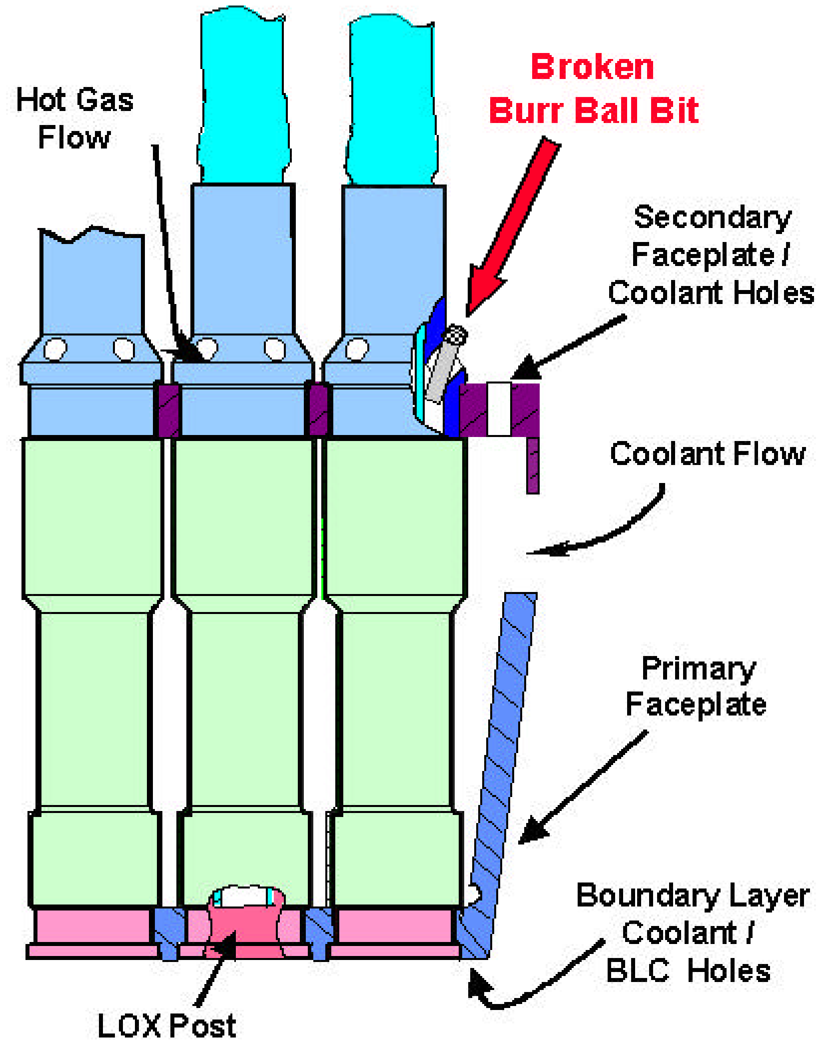
SSME Powerhead / MCC / HPTPs



Burr Ball Bit Geometry



Max. mass of broken
burr ball bit = .5 grams



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E2052 Foreign Object Debris

Broken Burr Ball Bit - Investigation

- **Unable to determine timing or specific operation being performed when bit broken**
  - Boundary Layer Coolant hole drilling most probable event
    - BLC holes maintain adequate cooling of MCC hot gas wall
      - Operation can be done at Canoga, SSC and KSC
      - 7 BLC holes required per design
      - Additional holes opened as needed (per specification and/or MR action)
    - BLC opening opportunities on E2052 / E2039
      - 12 BLC holes opened in June '95 (10 tests / flights since)
      - 7 BLC holes opened in February '99 (5 tests / flights since)
    - Operation improved in May '99
      - Standard drill bit replaced burr ball bit

E2052 Foreign Object Debris

FOD Assessment - Broken Burr Ball Bit

- **All potential migration paths evaluated**
  - Limited paths due to piece size and geometry
- **Engine Coolant Circuit unaffected**
  - Minimal blockage potential
    - Worst case - isolated LOX post tip erosion (Crit 3)
- **Impact potential minimal**
  - Inadequate energy to cause damage
    - LPF discharge duct, HGM coolant duct and liner, fuel sleeves
  - Migration out BLC holes during operation
    - Potential to strike and rupture two nozzle tubes
    - No significant affect on engine performance, redline margins and ability to complete mission
  - Migration to HPTP turbines in zero g environment
    - Verified clean pre-flight with visual inspections and torque checks
    - Below safe impact size for heat exchanger

E2052 Foreign Object Debris

General Engine FOD Assessment

- **SSME Designed for Tolerance to FOD**
  - Inlet filters to screen out FOD prior to entry
    - Orbiter / tank, ASI, GOX, hydraulic, pneumatic
  - Multiple element injectors
  - Components with multiple passages, annuluses and manifolds
  - Shielding as necessary (LOX post elements at hot-gas inlet of Main Injector)
- **Extensive Ingestion History**
  - Extensive successful hot fire experience validates engine FOD tolerance
    - > 2900 starts / > 955,000 seconds
  - Exceptional tolerance to impact damage, of primary concern is FOD with potential for extensive system blockage

E2052 Foreign Object Debris

General Engine FOD Assessment

- **Ground Test Validation and In Service Reviews and Inspections**
  - Engine Acceptance Tests and Component Green Runs
    - Verify performance and structural integrity prior to delivery
    - Required of all major components
  - Performance and operational data review
    - Conducted after each hot fire test and flight
    - Tracked versus requirements and also trend analyses to confirm “within family”
  - External and internal pre-flight engine inspections
    - Per OMRSD and/or special requirements via RAR

E2052 Foreign Object Debris

General Engine FOD Assessment

- **Order of magnitude reduction in occurrences of FOD in last 10 years**

- **Increased Employee Awareness and Sensitivity**
  - Design Changes
  - Fabrication Improvements
  - Facility Upgrades
  - FOD Sources Controlled
  - Inspection Techniques Enhanced
  - Process / Planning Reviews focused on FOD prevention and control
  - Employee Ownership and Culture Change

E2052 Foreign Object Debris

- **Rationale for Flight**
  - Broken Burr Ball Bit
    - Limited potential to break a bit on flight engines
    - All potential migration paths evaluated with no significant effect on engine operation
      - Cooling capabilities unaffected
      - Minimal impact damage potential
  - General FOD
    - SSME designed for tolerance to FOD
    - Ground test program and in service reviews and inspections validate hardware integrity prior to flight
    - Extensive successful hot fire history
    - Increased employee awareness

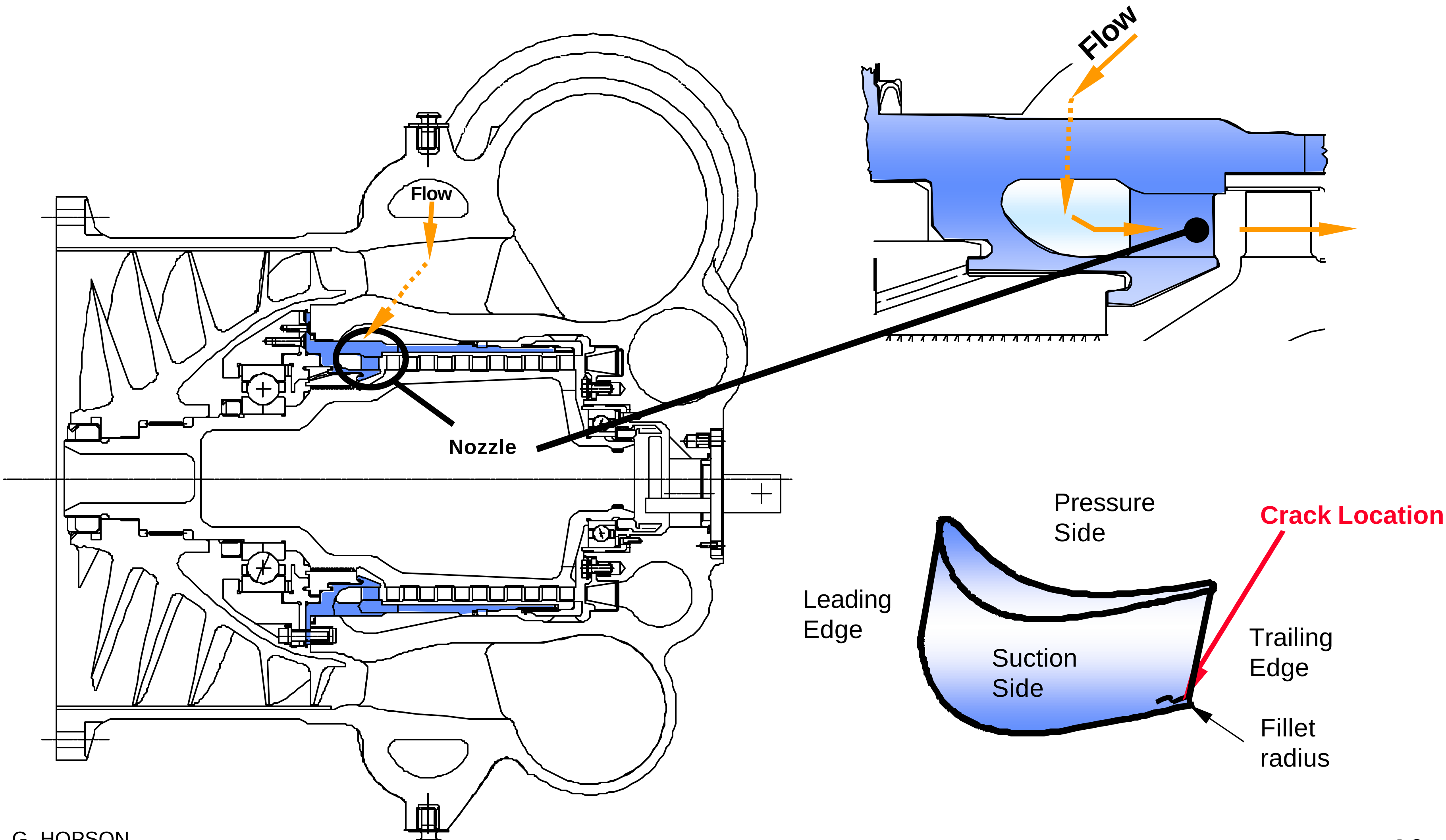
LPOTP Nozzle Vane Cracking

- **Issue**
  - Cracking of nozzle vane trailing edge fillet radii discovered in moderate time LPOTP nozzle
- **Background**
  - Penetrant inspection being completed as part of Block II retrofit
    - S/N 4877663: 20 starts / 7642 seconds
  - Two prior occurrences of HCF induced vane cracks

    1) 16 vanes cracked (96 starts / 36,529 seconds)

    2) 2 vanes cracked (82 starts / 34,819 seconds)
    - Existing life limit per DAR 2956
      - Life limited to 18,129 seconds (50% fleet leader)
      - Penetrant Inspect at 9064 seconds (25% fleet leader)

LPOTP Nozzle Vane Cracking

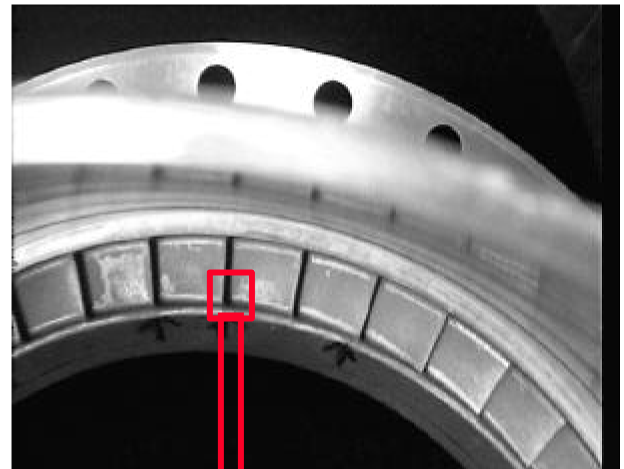


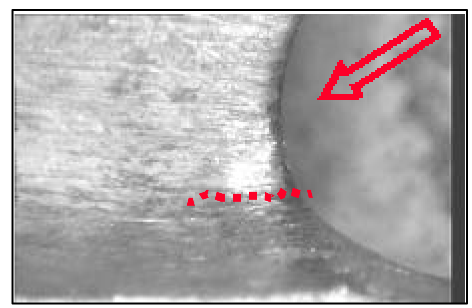
LPOTP Nozzle Vane Cracking

Materials Analysis (S/N 4877663)

- **Crack Verified by Sectioning**
  - Trailing edge through wall
    - Pressure side length = .107”
    - Suction side length = .065”
  - Pressure side initiation with apparent stable crack growth through to suction side
    - HCF initiation and propagation
      - Multiple initiation sites
    - No evidence of crack growth towards vane leading edge
    - Crack remains in vane fillet radius
    - Very little smearing of fracture surfaces
      - Suggests little relative displacement between fracture surfaces

Nozzle Vane Assembly Upstream View





Trailing Edge, Cracked Vane

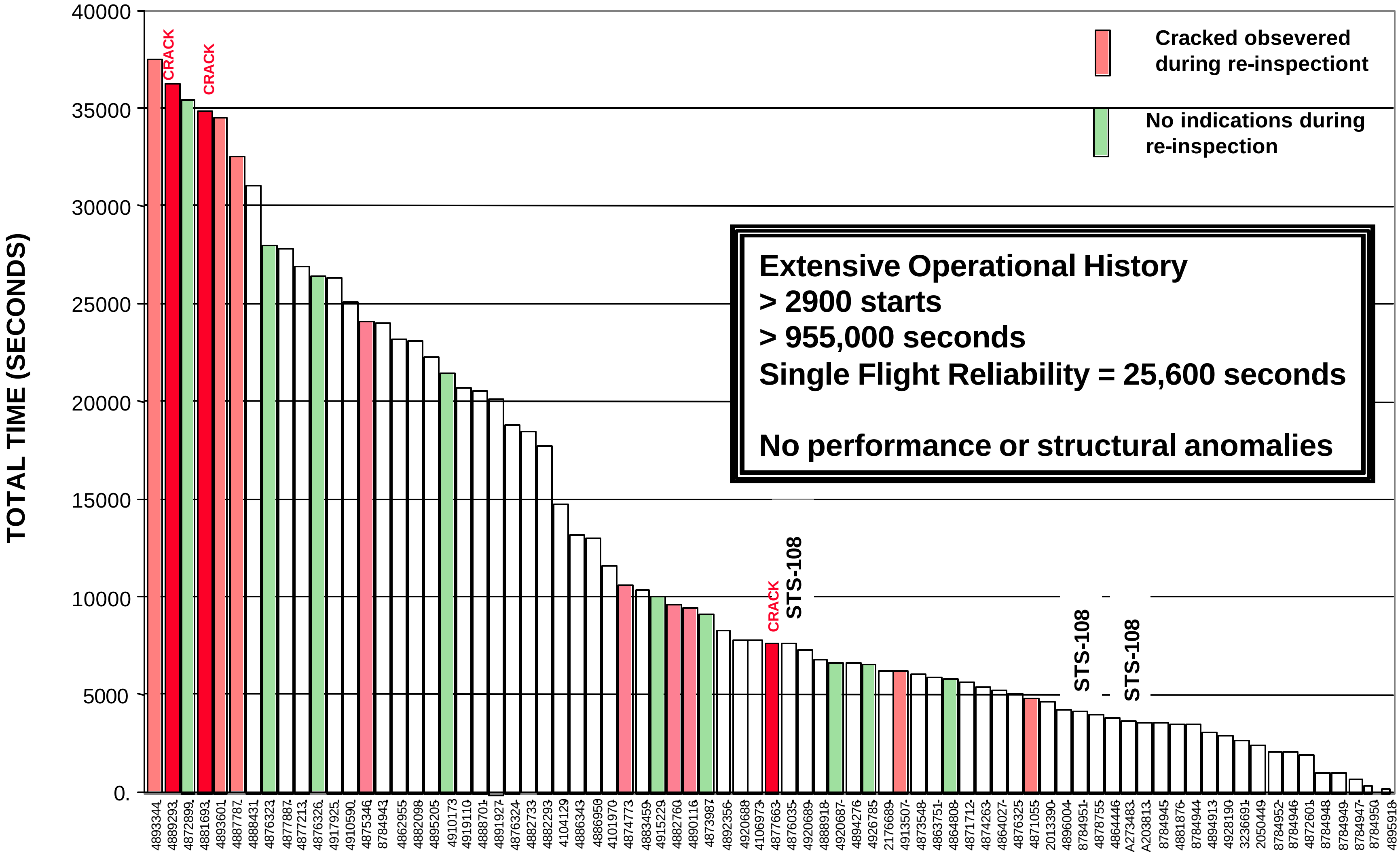
LPOTP Nozzle Vane Cracking

Fabrication Process / Investigation

- **Casting and Fabrication Process**
  - Unchanged throughout program history
    - Not uncommon to require some blending of trailing edge radii to remove suspected casting defects
- **Investigation / Reinspections**
  - Additional penetrant inspections completed (heightened sensitivity to entire vane fillet radius)
    - Cracks characterized as “tight”
    - Pressure side of vane (crack initiation site) is “hidden surface” not normally inspected
  - Cracking noted in 9 of 18 vane assemblies (50 total vanes)
    - Range in operational times from 4773 seconds to 37,500 seconds (fleet leader)
  - Most all cracking located on trailing edge ID fillet radii
    - Some indications at trailing edge OD fillet radii

LPOTP Nozzle Histogram

Units Re-Inspected



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LPOTP Nozzle Vane Cracking

Structural Assessment

- **Preliminary analyses support tolerance to large trailing edge defects**
  - Static Stress Assessment
    - Operational pressure is primary loading
    - Nominal stress state relatively low
      - Some peaking at both leading and trailing edges
  - Dynamics Assessment
    - Vane natural frequency is very high (~35kHz)
      - Well out of range of possible excitation sources
    - Quasi-static vane response to any dynamic loading (no amplification of dynamic loading)
      - Significant peaking at trailing edge with rapid decay
  - Fracture Mechanics Assessment
    - Initial parametric analysis shows tolerance to large defects
    - Critical Initial Flaw Size (CIFS) > .300”

LPOTP Nozzle Vane Cracking

Additional Actions In Work

- **Vane Inspections**
  - Penetrant inspection of all remaining available nozzles
    - Including pressure side fillet radii
  - Dimensional inspection of representative sample of vanes
    - Including vane thickness and fillet radius
- **Materials Analyses**
  - Additional sectioning of indications from other nozzles
    - Confirm HCF cracking mechanism
- **Structural Analysis**
  - Completion of refined analysis
  - Verify tolerance to defects and structural margins

LPOTP Nozzle Vane Cracking

- **Preliminary Rationale for Flight**
  - Extensive operational history with no performance or structural anomalies
    - Focused reinspection confirms cracking in 9 of 18 vane assemblies (50 total vanes)
    - Single Flight Reliability = 25,600 seconds
  - Structural analysis supports tolerance to large defects
    - CIFS > 0.300” (max measured size = ~.200”)
    - Consistent with fractography - no evidence of crack growth towards leading edge

Endeavour STS-108

Significant MR/PR Review

	2049		2043		2050	
	MRs	PMRB*	MRs	PMRB*	MRs	PMRB*
Powerhead	86	39	102	52	134	71
MCC	20	9	31	13	19	8
Nozzle	110	75	103	44	87	46
Controller	1	0	0	0	4	0
HPFTP	207	89	168	82	196	35
LPFTP	66	30	64	27	67	28
HPOTP	240	81	148	64	173	62
LPOTP	38	15	36	16	48	12
Assembly Ops	123	49	126	46	167	62
Ducts/Interconnects	106	71	95	63	119	81
Totals	**997**	**458**	**873**	**407**	**1014**	**405**

Total PMRB MRs = **1270**

Total MRs = **2884**

*MRs that would meet today's Rocketdyne PMRB criteria

All dispositions reassessed and found acceptable for flight.

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SSME Certification of Flight Readiness

- **Flight Readiness Review CoFR Exception**
  - UCR A034411 - LPOTP Nozzle Vane Cracking
    - Investigation and analysis ongoing
    - Finalized rationale for flight to be presented at Prelaunch Mission Management Team review

Endeavour STS-108

SSME Readiness Statement

- **The Endeavour Main Engines are in a ready condition for STS-108 pending completion of open work.**

G.D. Hopson

Manager
SSME Project

J. S. Paulsen

Program Manager
Space Shuttle Main Engine